PRELIMINARY PERFORMANCE RESULTS OF A HIGH-CURRENT Cs-Ba TACITRON IN A SIMPLE INVERTER

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Abstract

A tacitron[1,2] is a gas-discharge triode that is designed to be completely grid-controlled. Demountable cesium-barium (Cs-Ba) tacitrons have exhibited very low forward voltage drops in the range of a few volts, hold-off voltages greater than 200 V, and average conduction current densities greater than 10 A/cm^2. These characteristics yield an average power switching density on the order of 10^3 W/cm^2 in excess of 95% peak switching efficiency[3]. This parameter regime places the Cs-Ba tacitron in the range of conventional solid-state devices, with the advantage that the tacitron should reliably operate in extremes of temperature and radiation. The intent of this investigation is to determine the feasibility of constructing a 6 kW continuous power inverter unit with a pair of high-current tacitrons.

Introduction

The principle motivation for investigating Cs-Ba tacitron technology has been its potential for use in the inversion of dc electrical power from a high-temperature direct thermal-to-electrical energy converter (e.g., a space nuclear power system). Tacitron inverter operation at low average power (0.1 kW at a 25 V collector bias) has been previously studied at the University of New Mexico's Institute for Space Nuclear Power Studies[4-11]. Using a pair of demountable high-current Cs-Ba tacitrons (HCTs) that have been recently designed and fabricated at the Russian Scientific Center, Kurchatov Institute, the University of New Mexico's Pulsed Power and Plasma Sciences Laboratory is conducting measurements of high-current tacitron inverter performance in the kilowatt power range. Preliminary conclusions are drawn by a comparison between the inverter performance of the high-current tacitrons and that of the low-current Cs-Ba tacitrons previously studied at UNM-ISNPS. The high-current tacitrons have nominal planar emitter areas of 28 cm^2 versus the 2 cm^2 surfaces of the low-current tacitrons, and a similar system of external cesium and barium reservoirs whose temperature (i.e., vapor pressure) is regulated via separate heaters.

Description of High-Current Cs-Ba Tacitron Inverter Circuit and Test Stand

Emitter and collector planar surface areas of the high-current Cs-Ba tacitron are 28 cm^2 and 27 cm^2, respectively. The grid is a 65% transparent honeycomb design, with the same planar area as the emitter, and a thickness and aperture diameter of approximately 1.5 mm and 1 mm respectively. Grid-collector and grid-emitter electrode separations are roughly 1.5 mm, with the grid located near the center of the emitter-collector gap. Peak measured emission is 9 A/cm^2 at a forward voltage (conduction) drop of 5.5 V. Voltage hold-off exceeds 125 V at a Cs vapor pressure of 4×10^{-3} Torr (using a 3.6-msec half-sine pulse to the collector while the grid is grounded)[15]. External reservoirs allow cesium and barium pressures to be controlled independently of emitter temperature. A more detailed description of the high-current Cs-Ba tacitron is given in ref. [15].

Inverter operation depends critically upon the performance of the grid trigger circuit, which must reliably ignite the discharge in one tacitron while extinguishing the discharge in the second tacitron. The grid trigger

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14. ABSTRACT
A tacitronl121 is a gas-discharge triode that is designed to be completely grid-controlled. Demountable cesium-barium (Cs-Ba) tacitrons have exhibited very low forward voltage drops in the range of a few volts, hold-off voltages greater than 200 V, and average conduction current densities greater than 10 A/cm2. These characteristics yield an average power switching density on the order of 103 W/cm2 in excess of 95% peak switching efficiencyl31. This parameter regime places the Cs-Ba tacitron in the range of conventional solid-state devices, with the advantage that the tacitron should reliably operate in extremes of temperature and radiation. The intent of this investigation is to determine the feasibility of constructing a 6 kW continuous power inverter unit with a pair of high-current tacitrons.

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circuit has been designed and built to provide ignition and extinguishing grid pulses of up to 85 V in amplitude at peak currents of 50 A. Modulation frequency can be varied in the range $f_m = 2 - 10$ kHz, and grid pulse risetime is 100 ns into a non-reactive load. Typical risetimes in preliminary modulation tests with the HCT are 220 ns. Grid pulse duration can be varied in the range 10 – 50 μsec, and pulse duration and amplitude can be set independently for both the ignition pulse and the extinguishing pulse. Each of the two tacitrons in the inverter circuit will have an individual grid trigger circuit that can be set up independently of the other. The trigger circuits will be slaved together for inverter timing purposes. The full master-slave inverter trigger circuit is not yet complete, so the present discussion will be limited to the modulation performance of a single high-current Cs-Ba tacitron (HCT).

The inverter load, designed to handle a continuous dissipation of 6 kW, consists of five 1 kW, 300-Ω Cesiwid (formerly Carborundum) non-inductive resistors in parallel. A water-cooled container full of mineral oil removes heat from the 60-Ω load. The pulse transformer was custom made by Western Transformers, Inc., to meet the following specifications:

Primary Voltage, V_{cc} (V)	Secondary Taps, $V_{pk\text{-}pk}$ (V)	P_e (kW)	f (kHz)
20	330, 360, 390, 420, 450, 480, 510, 540, 570	6	1 to 20

The test stand consists of a vacuum chamber with a base pressure of 10^{-7} Torr and feedthroughs for emitter, base flange, Ba reservoir, and Cs pipeline heater leads. Feedthroughs are also provided for thermocouples, collector and emitter bias power leads, grid control leads, and the Cs pipeline that runs between the external Cs reservoir and the HCT base flange.

Data acquisition and control consists of an 80486 PC running a custom software application written in the National Instruments LabWindows development environment. The acquisition and control application is interfaced to a LeCroy 9304 (4-channel) 175 MHz digital oscilloscope for current and voltage measurements and an ADAC Corp. 5302EN I/O module for thermocouple measurements and I/O control signals. Uncertainty in relative temperature measurements is approximately 5° C for the emitter and 2° C for all others. Modulation currents are measured using Pearson Electronics, Inc., wide-band current transformers.

Experimental Results

Acceptable inverter operation requires that the inverter switches reliably ignite and extinguish on demand. Prior to testing the inverter performance of the high-current demountable Cs-Ba tacitron (HCT), it is necessary to define the parameter space over which the switch will reliably modulate. Waveforms from preliminary modulation tests of the high-current demountable Cs-Ba tacitron (HCT) are given in Fig.s 1 – 4. Modulation parameters from these tests have been listed in Table I. There is a serious limitation apparent in these data that are not indicative of fundamental limitations in HCT performance: low collector bias V_{cc}. The low collector bias limits the magnitude of the discharge current, but is necessary to prevent self-ignition of the HCT, since the present implementation of the grid trigger circuit allows the grid to float at near collector potential. While this preliminary data is not a good indication of HCT power switching capability, it does provide insight into the switching times achievable with a Cs plasma device.

The waveforms of Fig.s 1 – 3 were taken at similar device operating points, but different modulation frequencies (3.7 kHz for Fig. 1 and 12 kHz for Fig. 2). Notable differences in performance are that the device is more difficult to ignite and easier to extinguish at the higher frequency, and the forward voltage drop is greater (4.4 V versus 4.1 V) at the higher f_m. The ignition voltage at 12 kHz increases from 68 V to 86 V, while the collector current fall (extinguishing) time decreases from 20 μs at 3.7 kHz to 1.5 μs at 12 kHz. These effects are attributable to a lower effective plasma density in the discharge region at the higher frequency, and could be mitigated by increasing the Cs pressure at higher modulation frequencies. The topology of the grid trigger circuit is such that grid current cannot be measured unless the output stage of the trigger is conducting, indicating that the

167 MHz oscillation evident during conduction at f_m = 3.7 kHz is due to feedback between the grid and the grid trigger circuit under certain operating conditions. A comparison between Fig.s 2 and 3 indicate that HCT ignition times are relatively unaffected by the modulation frequency, implying that switching efficiency will suffer as modulation frequency increases.

Fig. 4 contains a set of modulation waveforms taken at higher cesium reservoir temperature, but similar emitter and barium reservoir temperatures, and modulation frequency, as those of Fig. 1. The higher T_{Cs} requires a lower grid ignition voltage V_{g+} and collector bias V_{cc} (7.24 V versus 14.5 V), and results in lower forward voltage drop V_f (3.1 V versus 4.1 V) and a larger conduction current fall time t_{fc} .(28 μs versus 20 μs). The lower required ignition voltage (40 V versus 69 V) results in a larger ignition delay time t_{d+} (20 μs versus 9.3 μs) and a lower ignition current I_{g+} (11 A versus 21 A). The collector bias V_{cc} has been reduced in order to prevent self-ignition at the higher Cs pressure, due to the floating grid.

Discussion and Conclusions

The high-current demountable Cs-Ba tacitron has demonstrated controlled modulation at reduced power, but is not yet sufficently well characterized to place in a high-power inverter circuit. Data for comparison is limited, but it appears that the extinguishing time of t_{fc} = 1.5 μs at f_m = 12 kHz is comparable to the extinguishing time of a previously investigated triangular aperture grid tacitron[11] whose grid is similar in construction to that of the HCT. Stable current modulation of the triangular aperture grid device was achieved for Cs reservoir temperatures in the range T_{Cs} = 140 –154° C (5.2 – 10 × 10^{-3} Torr), versus T_{Cs} = 130 –145° C (3.1 – 6.7 × 10^{-3} Torr) for the HCT. The physical size of the HCT does not appear to limit the extinguishing time. Collector current risetimes in the range 26 μs to 38 μs, for collector biases ranging from 7.2 V to 14.5 V, are somewhat longer than those of a previously investigated cylindrical Cs-Ba tacitron which had a 15 μs collector current risetime at a 140 V collector bias. This may be largely due to the differences in collector bias, however.

Table I. Modulation parameters from preliminary tests of the high-current demountable Cs-Ba tacitron.

Parameter	Symbol	SC623-03	SC623-12	SC623-19	SC623-25
Emitter temperature	T_E	1038° C	1033° C	1033° C	1030° C
Barium reservoir temperature	T_{Ba}	554° C	554° C	554° C	552° C
Cesium reservoir temperature	T_{Cs}	134° C	134° C	134° C	141° C
Modulation frequency	f_m	3.7 kHz	12 kHz	12 kHz	4.0 kHz
Grid ignition pulse voltage	V_{g+}	+68 V	+86 V	+86 V	+40 V
Grid extinguishing pulse voltage	V_{g-}	–83 V	–83 V	–85 V	–85 V
Grid ignition pulse duration	t_{g+}	52 μs	15 μs	35 μs	52 μs
Grid extinguishing pulse duration	t_{g-}	44 μs	9 μs	28 μs	47 μs
Grid ignition pulse current	I_{g+}	21 A	25 A	44 A	11 A
Grid extinguishing pulse current	I_{g-}	6.0 A	2.7 A	2.1 A	2.1 A
Grid ignition pulse current risetime	t_{rg+}	16 μs	13 μs	14 μs	22 μs
Collector bias voltage	V_{cc}	14.5 V	13.8 V	12.6 V	7.24 V
Conduction voltage drop	V_f	4.1 V	3.7 V	4.4 V	3.1 V
Conduction current, peak / mean	I_c	54 A / 41 A	53 A / 29 A	47 A / 27 A	21 A / 15 A
Collector current risetime	t_{rc}	37 μs	24 μs	26 μs	38 μs
Collector current fall time	t_{fc}	20 μs	0.7 μs	1.5 μs	28 μs
Ignition delay time	t_{d+}	9.3 μs	8.6 μs	9.5 μs	20 μs
Extinguishing delay time	t_{d-}	3.0 μs	1.2 μs	1.2 μs	1.3 μs

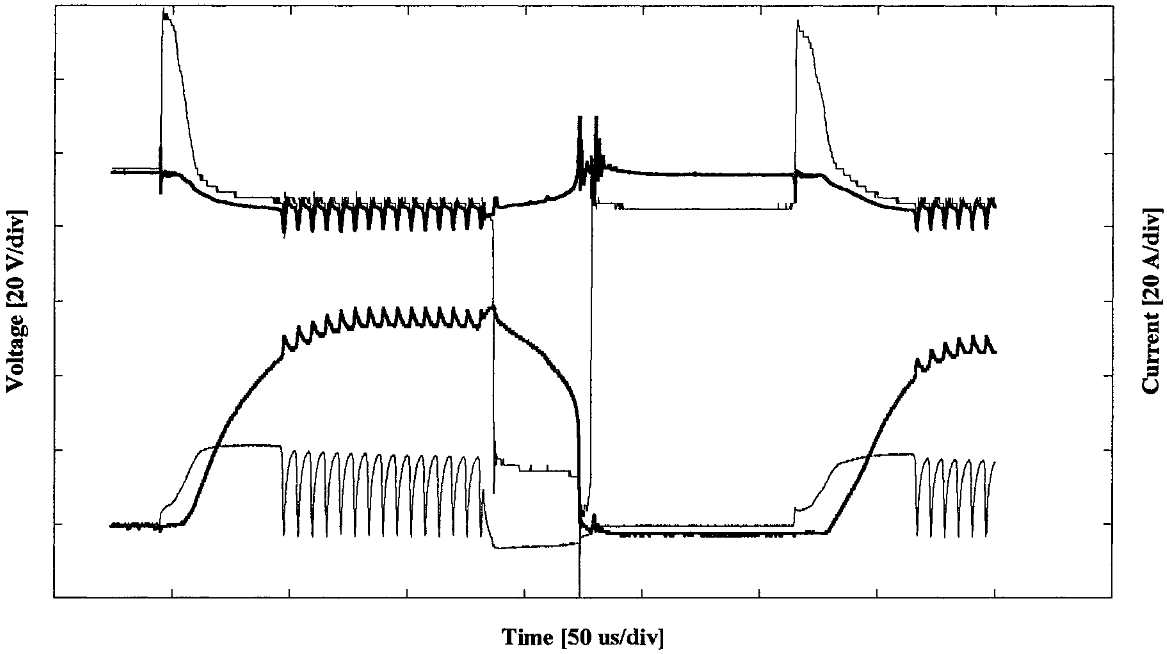

Fig. 1. Modulation test SC623-03 of the high-current prototype tacitron taken at device conditions T_E = 1038° C, T_{Ba} = 554° C, and T_{Cs} = 134° C (4 x 10^{-3} Torr). Grid (fine) and collector (bold) voltage waveforms are at the top of the figure, while grid (fine) and collector (bold) current waveforms are at the bottom.

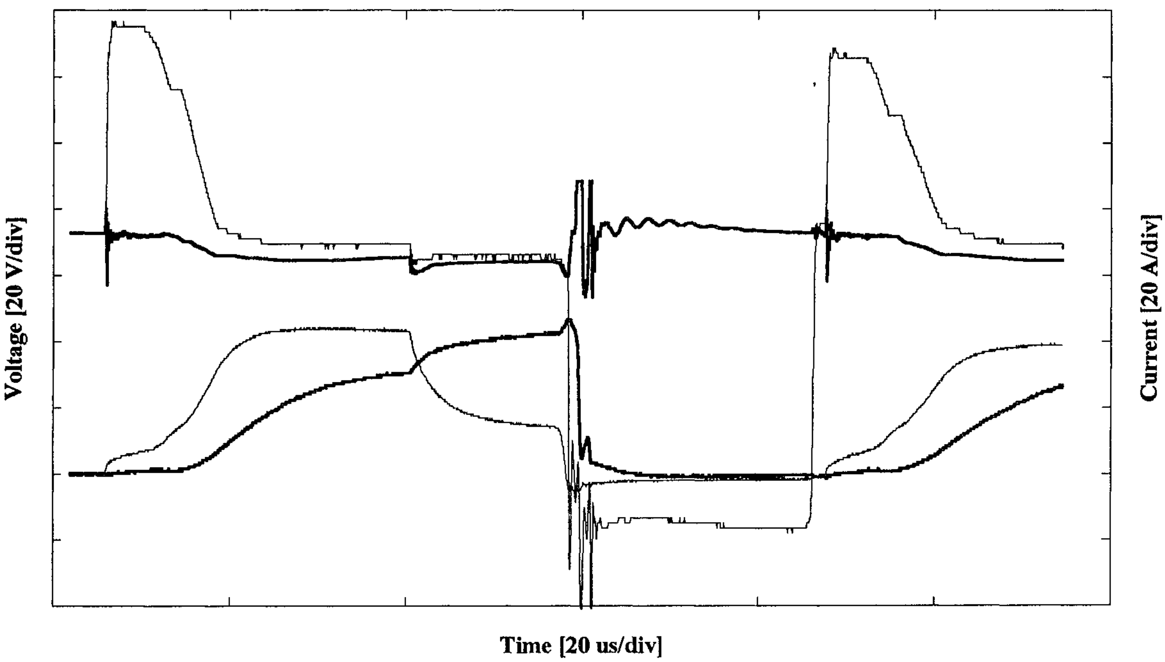

Fig. 2. Modulation test SC623-19 of the high-current prototype tacitron taken at device conditions T_E = 1033° C, T_{Ba} = 554° C, and T_{Cs} = 134° C (4 x 10^{-3} Torr). Grid (fine) and collector (bold) voltage waveforms are at the top of the figure, while grid (fine) and collector (bold) current waveforms are at the bottom.

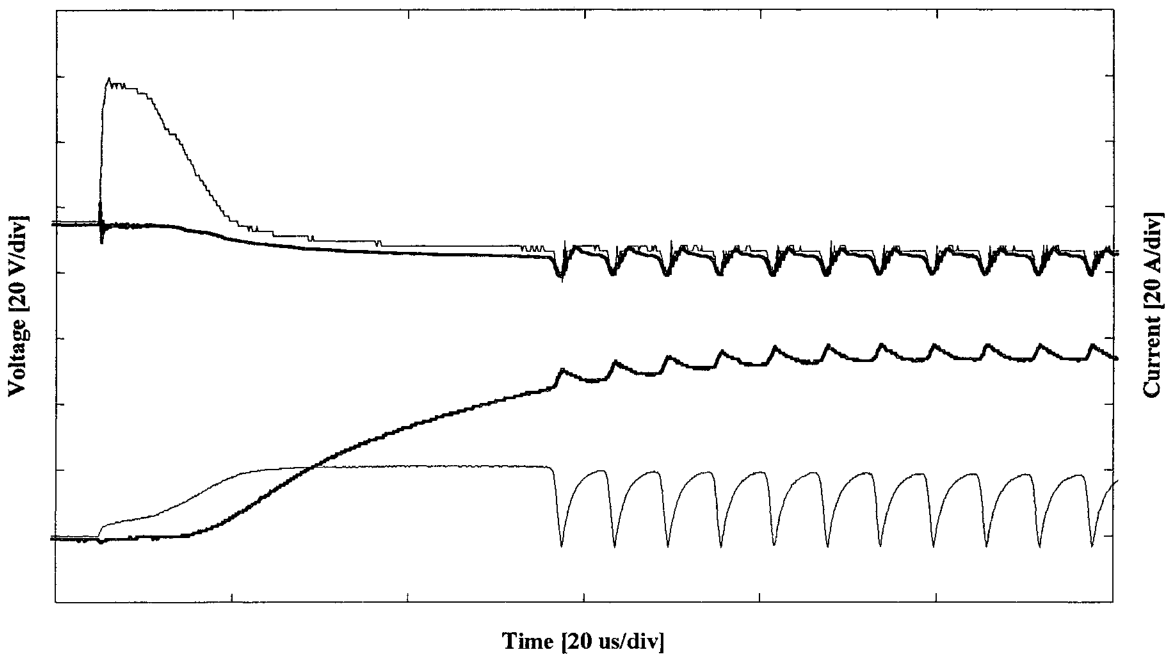

Fig. 1a. Modulation test SC623-03 of the HCP (same as Fig. 1 except scaled for comparison to Fig. 2).

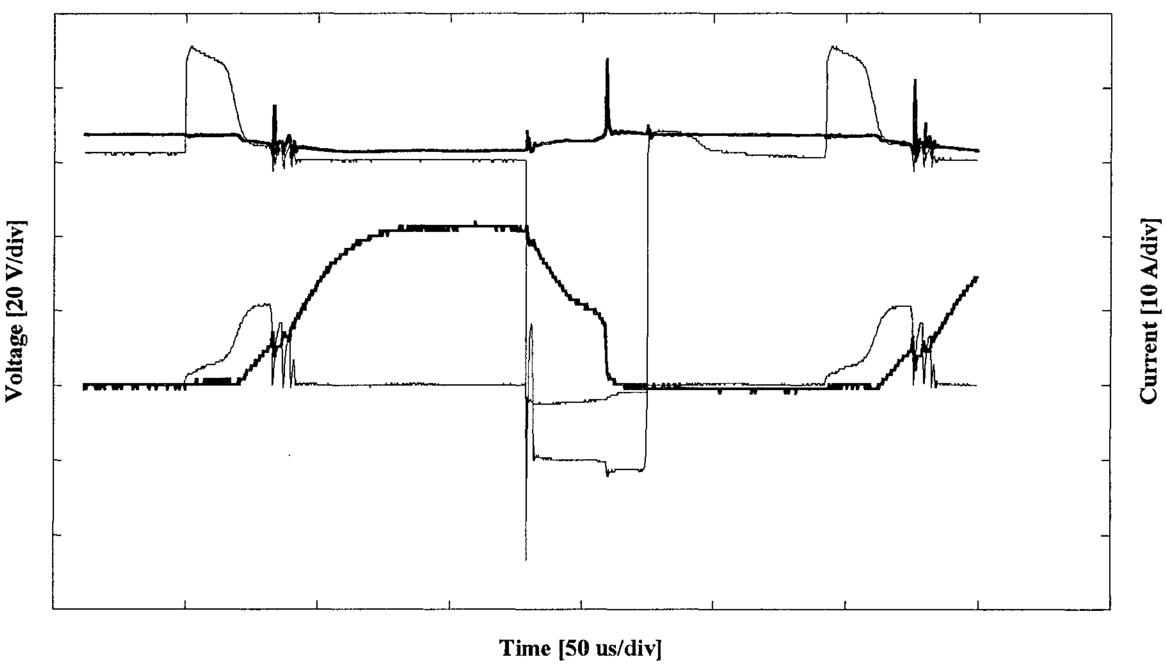

Fig. 3. Modulation test SC623-25 of the high-current prototype tacitron taken at device conditions $T_E = 1030°$ C, $T_{Ba} = 552°$ C, and $T_{Cs} = 141°$ C (5.5×10^{-3} Torr). Grid (fine) and collector (bold) voltage waveforms are at the top of the figure, while grid (fine) and collector (bold) current waveforms are at the bottom.

The high transparency (65%) of the HCT honeycomb grid requires a relatively low Cs pressure, in the range $2 - 7 \times 10^{-3}$ Torr (T_{Cs} in the range 125 – 145° C), to achieve reliable discharge extinction and to prevent self-ignition at collector biases, V_{cc}, greater than approximately 10 – 20 V. Wernsman, et al.[10], indicate that a grid with 34% transparency and 0.5 mm diameter apertures yields good ignition and extinguishing performance, with a reasonably low conduction drop.

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References

[1] V. Z. Kaibyshev, G. A. Kuzin, and M. V. Mel'nikov, "Use of the Thermionic Converter for Regulation of Current in Electric Circuits," *Soviet Physics Technical Physics*, Vol. 17, No. 6, pp. 1006-1009, 1972.

[2] E. O. Johnson, J. Olmstead, and W. M. Webster, "The Tacitron, a Low Noise Thyratron Capable of Current Interruption by Grid Action," *Proceedings of the IRE*, Sep., 1954.

[3] V. Z. Kaibyshev and G. A. Kuzin, "Effect of a Third Electrode on a Low Voltage Arc," *Soviet Physics Technical Physics*, Vol. 45, No. 2, pp. 320-327, 1975.

[4] M. S. El-Genk, C. Murray, and S. Chaudhuri of ISNPS, and V. Kaibyshev, A. Borovskikh, Y. Djashiashvili, and Y. Taldonov of the Kurchatov Institute, "Experimental Evaluation of Cs-Ba Thermionic Switch/Inverter -- 'Tacitron'," *Proceedings of the IECEC*, Boston, MA, Aug. 4-9, 1991.

[5] M. S. El-Genk, C. Murray, and Glen McDuff of ISNPS, and V. Kaibyshev, A. Borovskikh, Y. Djashiashvili, and Y. Taldonov of the Kurchatov Institute of Atomic Energy, "Peculiarities of the Discharge Breakdown of the Cs-Ba Tacitron," *Proceedings of the 2nd Thermionic Specialist Conference of the USSR*, Sukhumi, USSR, Oct. 28 - Nov. 2, 1991.

[6] C. Murray, B. Wernsman, and M. S. El-Genk of ISNPS, and V. Kaibyshev of the Kurchatov Institute of Atomic Energy, "Ignition and Extinguishing Characteristics of Cs-Ba Tacitron," *Journal of Applied Physics*, Vol. 72, No. 10, 15 Nov. 1992.

[7] M. S. El-Genk, V. Kaibyshev, C. Murray, B. Wernsman, and Y. Djashiashvili, "Effect of the Grid Aperture on the Operation of the Cs-Ba Tacitron Inverter," *Proceedings of the IECEC*, San Diego, CA, Aug. 3-7, 1992.

[8] B. Wernsman and M. S. El-Genk, "Experimental Investigation of Current Modulation in a Planar Cs-Ba Tacitron," *IEEE Transactions on Electron Devices*, Apr. 1994.

[9] B. Wernsman, M. S. El-Genk, and V. Z. Kaibyshev, "Experimental Investigation and Analysis of the Operation Characteristics of a Planar Cs-Ba Tacitron," *11th Symposium on Space Nuclear Power and Propulsion*, Jan. 9-13, 1994, Albuquerque, NM.

[10] B. Wernsman and M. S. El-Genk, "Modulation Capabilities of Different Grid Designs for a Cs-Ba Tacitron," *21st International Power Modulation Symposium*, Jun. 28-30, Costa Mesa, CA, 1994.

[11] I. Djachiachvili and M. S. El-Genk, "Investigation of Triangular Aperture Grid for Plasma Switch Devices," *21st International Power Modulation Symposium*, Jun. 28-30, Costa Mesa, CA, 1994.

[12] C. Murray, M. S. El-Genk, B. Wernsman, and V. Kaibyshev, "A Steady-State Model for a Low-Pressure Cs-Ba Diode," *Journal of Applied Physics*, Vol. 74, No. 1, 1 Jul. 1993.

[13] C. Murray, M. S. El-Genk, and V. Kaibyshev, "Steady-State Model of a Low Cs Pressure Discharge in a Triode," *11th Symposium on Space Nuclear Power and Propulsion*, Albuquerque, NM, Jan. 9-13, 1994.

[14] J. Luke and M. S. El-Genk, "A Transient Model of a Cs-Ba Diode," *11th Symposium on Space Nuclear Power and Propulsion*, Albuqurque, NM, Jan. 9-13, 1994.

[15] G. B. Masten, I. Djachiachvili, D. B. Morris, and J. M. Gahl, "Operating Characteristics of a High-Current Demountable Cs-Ba Tacitron," *10th IEEE Pulsed Power Conference*, Albuquerque, NM, July 10-13, 1995.

[16] B. Wernsman and M. S. El-Genk of ISNPS, and V. Kaibyshev of the Kurchatov Institute of Atomic Energy, "Operation Characteristics of Planar Cs-Ba Tacitron," *Rev. Sci. Instrum.*, Apr. 1994